A Sensor Array System for Monitoring Moisture Dynamics in Unsaturated Soil

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ABSTRACT

To facilitate investigations of moisture dynamics in unsaturated soil, we have developed a technique to qualitatively monitor patterns of saturation changes. Field results suggest that this device, the sensor array system (SAS), is suitable for determining changes in relative wetness along vertical soil profiles. The performance of these probes was compared with that of the time domain reflectometry (TDR) technique under controlled and field conditions. Measurements from both techniques suggest that by obtaining data at high spatial and temporal resolution, the SAS technique was effective in determining patterns of saturation changes along a soil profile. In addition, hardware used in the SAS technique was significantly cheaper than the TDR system, and the sensor arrays were much easier to install along a soil profile.

Abbreviations: SAS, sensor array system; TDR, time domain reflectrometry; OD, outer diameter; PVC, polyvinyl chloride

INTRODUCTION

Two fundamental parameters are commonly used to describe water in soil, i.e., the amount of water (content) and the energy state of water (potential). Soil water content and potential are separately measured by a number of techniques, and detailed reviews of such techniques can be found in recent journal articles and soil physics textbooks (e.g., Raats, 2001; Topp and Ferre, 2002; Hillel, 1998). However, there are four main drawbacks with the existing methods used to measure content or potential of *in situ* soil water: (1) disruptions to the measured environment, (2) calibration requirements, (3) equipment costs, and (4) difficulty of *in situ* installations. In addition, some established techniques, such as the neutron scattering method, are time consuming, while others, such as the traditional gravimetric method, do not allow for repeated measurements on the same volume of soil.

Thus, with current techniques, not only is the spatial and temporal extent of measurements limited, but often an accurate assessment of the amount or energy status of soil moisture remains unattainable. An important consequence of current limitations is that with increasing numerical modelling capabilities, the vertical and lateral variation in soil moisture through seasons is emerging as a great unknown. This lack of data inhibits our ability to develop a realistic understanding of soil moisture dynamics and related ecological processes in the vadose zone.

One potential solution is to supplement absolute measurements of soil moisture (either content or potential) obtained using current methods with extensive information about the spatial and temporal *patterns* of the hydrological response. Since the spatial distribution of soil moisture can be thought of as a pattern that changes through time

(Wilson et al., 2004), techniques that can provide this pattern at low cost and with relative ease will allow us to examine the consequences of various processes on soil moisture dynamics.

In this paper, we present a new technique we have developed, the Sensor Array System (SAS), to monitor patterns of soil moisture changes in soil. The primary object of this effort was to develop an inexpensive tool that is easily deployed, to track saturation changes in soil at a high spatial (centimeters) and temporal (minutes) resolution. This paper describes the design of the prototype SAS and observations from two experiments that were conducted to evaluate the performance of this device.

DESIGN OF THE SENSOR ARRAY SYSTEM FOR MONITORING MOISTURE DYNAMICS

The main design concerns were to create (1) a sensor system that could detect saturation changes in multiple locations along a soil profile, (2) robust housing for an array of sensors, and (3) an installation technique that is quick and effective for placing the sensor system in soil.

Design of Sensor

The sensor used in SAS works on the principle that increasing amounts of water in a porous material results in decreasing electrical resistance in that material (*Archie*, 1942). To incorporate this relationship, we used filter paper as the sensing device, across which changes in electrical resistance could be measured (Salve et al., 2000). Individual sensors included two electrical leads located between pieces of filter paper (Figure 1A). The size of probes was a square with 0.01 m sides. (These probes can be further reduced or increased in size, depending on the application.)

Electrical resistance in each probe was determined through a half-bridge measurement. Here, a reference resistor (R_f) was introduced into the circuit to facilitate measurement of resistance across the sensing surface (R_s). A known voltage (V_i) was supplied to each sensor for a settling time of 0.1 s before the output voltage (V_x) was measured across the sensors. Using this configuration, the sensor resistance was calculated to be [*Campbell Scientific*, 1997]:

$$R_s = R_f \frac{X/V_x}{1 - X/V_x} \qquad (1)$$

where:

$$X = V_x \left(\frac{R_s}{(R_s + R_f)}\right) \qquad (2)$$

Resistance was measured from each probe with a datalogger [*Model CR10X, Campbell Scientific Inc., Logan, Utah*] that permitted half-bridge resistance measurements. A reference resistor (100 KΩ) was excited with a predetermined voltage (5 volts), and the output was incorporated into Equation (1) to obtain resistance across the sensor. Instructions to the datalogger were channeled through a computer, and the processed output (R_s) was directed to a storage module. To make measurements from a large number of sensors, we used multiplexers [*Model A416, Campbell Scientific Inc., Logan, Utah*] that were connected to the datalogger. Each multiplexer had the capacity to house 48 sensors. To prevent crosstalk between sensors, we measured only one sensor at a time, during which the circuit remained open for all other sensors. An internal check of the measurement system was continuously provided by precision resistors located randomly on the measurement ports of the multiplexers. Typically, the standard deviation from 1 KΩ and 100 KΩ precision resistor measurements were 0.001 and 0.005 KΩ, respectively.

Design of Sensor Housing

One key feature of this monitoring system is the use of multiple sensors, which are used to track saturation changes along a single profile (Figure 1B). The length of soil profile and the desired spatial resolution determine the number of sensors in a single array. For the prototype SAS, sensors were assembled at a spacing of 0.05 m along the length of a 0.025 m OD PVC tube. Once the probes were located, wires from each probe were routed inside the tube, and shrink tubing was placed over the sensors to protect the sensing surfaces during installation and to prevent preferential flow paths along the sensor array. Cutouts in the shrink tubing enabled contact of the sensor with the soil.

Installation of Sensors in Soil

To install the sensor arrays, we used a soil auger to create a ~0.04 m diameter borehole that extended to the desired length. The SAS stem was placed in the hole, and the space between the borehole and sensor was repacked with excavated soil. Soil removed from a certain depth was used to fill that particular depth, with care taken to maintain a similar packing density. In addition, at two depths, a layer of bentonite powder was introduced into the borehole to provide a seal that would prevent vertical flow caused by backfilling the borehole.

Costs Associated with Assembling the Prototype SAS

Costs associated with assembling the SAS prototypes developed for these preliminary tests include hardware (PVC tube, a few sheets of filter paper, and wiring). Additional costs were associated with a multiplexing unit and datalogger. Because there were twelve sensors in each stem, a single multiplexer could be used to monitor four stems (for a total of 48 sensors). Total costs for the prototype SAS and the price of the TDR system to measure a similar number of probes is presented in Table 1. The TDR costs are for a commercially available system (i.e., Model TDR100, Campbell Scientific, Inc.). This six-fold difference in measurement techniques does not include installation costs, which could also be significant if TDR probes were to be located at regular intervals to monitor multiple vertical soil profiles.

APPLICATIONS

Two tests were conducted to compare the performance of the SAS technique with the standard Time Domain Reflectometry (TDR) technique. In addition, consistency of measurement using our SAS method was also evaluated.

Since the 1980s, when Topp et al. (1980) pioneered its use, TDR has become a widely used method for water content measurements in soil (Sakaki and Rajaram, 2006). The rationale for using this electromagnetic technique to measure soil water content lies in its ability to exploit the large contrast between the dielectric properties of liquid water and those of dry soil at microwave frequencies (Brisco et al., 1992). This influence of water on the dielectric properties of porous media had been recognized for some time (e.g., Smith-Rose, 1933; Hallikainen et al., 1985; Zegelin et al., 1992). By determining the travel time of an electrical step pulse propagating in a transmission line embedded in a dielectric medium, Topp et al. (1980) calculated the apparent dielectric (K_a)of the medium. They then found that for a wide range of soil textures and porosities, the relationship between the moisture content and K_a are, to the first order, independent of soil texture and porosity. They derived a simple empirical third-order polynomial equation describing the relationship between the apparent K_a and moisture content. This relation has been shown to be accurate within a few percent for a wide variety of soils (Dalton, 1992). However, as cautioned by Roth et al. (1990), this relationship is also dependent on soil bulk density and the electrical conductivity of the pore water.

Soil moisture changes during and after a falling head release

The first test was conducted in a 0.60 m tall soil column contained in a 0.57 m ID PVC cylinder. Four individual SAS stems, each containing twelve sensors spaced 0.05 m apart, were each installed in the soil column 0.10 m from the edge of the column (Figure 2A). In addition, five TDR probes (each 0.30 m long and 0.05 m wide) were also installed horizontally at 0.10 m intervals along the height of the column. The soil used in the experiment was excavated from the Sedgwick Field Station in California, and packed with the 'A', 'B1', and 'B2' horizons each 0.20 m thick, at densities similar to those measured at the excavation site. An open-bottom 0.20 m diameter vertical infiltration cylinder was used to release ~18 L of water under falling head conditions at the surface into the soil profile. It took ~36 hours for the water to infiltrate, during and after which the TDR and SAS monitored saturation changes at 10-minute intervals.

Soil moisture changes during a series of rainfall events

The second test was conducted in the hills of Berkeley, California, where the SAS performance was compared with TDR probes under field conditions. Here, 0.075 m long TDR probes and SAS sensors were installed at three locations (Figure 2B). Two vertical holes, ~0.60 m deep with a diameter of 0.038 m, were augered at each location. The SAS stems were installed in a similar manner to those described in Section 2.3, whereas the TDR probes were installed vertically. Horizontal placement of the 0.075 m long TDR probes would have required a much larger hole, resulting in significantly more disturbance to the immediate environment of the installation boreholes.

OBSERVATIONS

Moisture dynamics in response to a falling head of water

TDR and SAS measurements began ~24 hours before water was released along the surface of the soil column and continued for the next 17 days. The sampling interval was 5 minutes, with the TDR system monitoring changes in the apparent dielectric constant of the soil and the SAS system measuring the resistance across the sensing surface. The TDR dielectric values were converted to soil moisture content using calibration equations developed for each of the three soil profiles.

TDR and SAS measurements from five depths along the soil profile are presented in Figure 3. In this figure, individual plots corresponding to a specific depth have been split to capture (1) the early wetting of soil during and immediately after the infiltration event, and (2) the distribution of the infiltrated water along the soil profile over the next fourteen days.

The general pattern of saturation changes in the soil column, as suggested by the TDR response, is an initial wetting and then some drying in the upper 0.38 m of soil. The TDR probe at the 0.08 m depth was the first sensor to detect the wetting front 15 minutes after water was introduced to the soil surface. With increasing depth, this arrival was also increasingly delayed, such that at 0.38 m, increased soil moisture was first detected 1935 minutes after the initial release of water. In the deeper profile (i.e., at depths >0.48 m) the soil moisture status remained unchanged.

Following the surface release of water, SAS sensors tracked changing soil moisture conditions similar to the TDR probes at all depths. A single exception was observed at the 0.08 m depth when—close to the last week of the monitoring effort—the SAS sensor measured small increases in soil moisture. While the TDR and SAS detected similar drying trends at each depth, a prominent difference was observed in their ability to detect variations in measurements from the general trend. Along the shallower depths, the SAS sensors showed a diurnal fluctuation that follows the air temperature changes. The TDR probe had a similar fluctuation, but superimposed were significant fluctuations between measurements taken at 5-minute intervals, as can been seen in the TDR measurements for the 0.38 m depth (Figure 3A).

There were two main differences (i.e., pattern of wetting and detection of wetting-front arrival time) in the response of the TDR and SAS at the shallow locations (up to a depth of 0.38 m) during and immediately after the release of water along the soil surface. The wetting pattern from the TDR probes suggests a gradual increase in soil saturation for the duration of the infiltration event, unlike the rapid increase measured by SAS sensors. This difference is likely a result of the TDR measurement at any given time representing an integrated soil moisture content for the entire volume of soil that was sampled—unlike the SAS sensors, which monitored changes over a 1 cm^2 sensing surface

At each of the monitored depths, the TDR detected an increase in soil saturation before the SAS sensors. At the 0.08 m depth, the difference between detection times was ~100 minutes, which increased to ~200 minutes at the 0.18 m depth and to ~350 minutes at the 0.38 m depth (Figure 4A). This difference is likely caused by the volume of soil accessed by each sensor and the difference in actual distance from the infiltration surface to the sensor at each horizontal plain. The soil "sampled" by TDR has the shape of a cylinder whose diameter is 1.4 times the spacing between the rods (Hillel 1998). In our case, this cross section had a diameter of 0.07 m, indicating that the TDR probe would have started to detect the wetting front when it was ~0.035 m above the actual plain along which the probes were located. This difference is illustrated in Figure 4B.

To evaluate the consistency of measurements by the SAS sensors, we compared the response patterns of the four SAS stems that monitored saturation changes during and after the infiltration event (Figure 5). The similar color patterns (indicating similar patterns of measured resistance) show that the four SAS stems were consistent in monitoring changes in soil moisture.

Soil Moisture Dynamics in response to natural rainfall events

The TDR and SAS systems were installed along a hill slope in Berkeley, California, on February 21, 2007, when this semi-arid region had received ~50 % of its anticipated rainfall. Over a seven-day period immediately after the sensors were installed, a series of short duration rainfall events occurred, during which 24.6 mm of precipitation was recorded. Rainfall two weeks later contributed to an additional 18.5 mm of precipitation, and over the next ~30 days, the site received ~20 mm of additional rain.

The TDR response shows that as monitoring began, the moisture content (as indicated by the measured apparent dielectric constant) along the vertical soil profile remained elevated, before gradually decreasing over the next 30 days. (Note that for this investigation, the soil-TDR relationship was not determined, and therefore all TDR readings are presented as the measured apparent dielectric constant.) Figure 6 shows that SAS sensors were able to track soil moisture changes similarly to the TDR.

Figure 7 is a representation of the saturation-change pattern (as indicated by the resistance measurements from the SAS sensors) along the three hillslope sites. The color gradients suggest that in each of the three sites, the rainfall events during the week of February 21, 2007, wetted the entire vertical profile, with more extensive wetting in the upper and middle site. The plots also show that the upper site began to dry earlier than the middle site, with saturation changes extending relatively uniformly across the monitored profile. Interestingly, along the profile of the relatively drier lower site, at two distinct depths (~0.20 and 0.45 m from surface), the drying pattern was different from the rest of the monitored profile, suggesting possible heterogeneity along this vertical soil profile.

SUMMARY

Soil moisture patterns in space and time play a key role in linking climate, vegetation, and hydrologic response and transport processes (e.g., Botter et al., 2007). Given the impracticalities of measuring soil moisture at high spatial and temporal resolution with existing techniques, the patterns of changes in soil moisture in space and time detected by the SAS technique suggests that this approach can be used effectively to provide insights about the near surface. The performance of this new technique was gauged largely on the performance the TDR technique, which is an established method to monitor soil moisture content. The parallels observed in the response patterns of these two monitoring systems (as indicated in Figure 6) suggest that the resistance patterns measured by SAS can be used to supplement point measurements provided by other methods. Our experiments have demonstrated that the SAS approach is effective and relatively cheap (~1/6th the cost of the TDR technique) for probing flow in the unsaturated soil environment. Perhaps the single most useful application of this devise is the spatial and temporal resolution at which saturation changes in the soil can be monitored. In addition, it is relatively easy to fabricate and installed SAS stems to custom-fit a vertical soil profile

While we have demonstrated (with this prototype SAS) the usefulness of this technique "as-is" in monitoring soil moisture dynamics, there are design modifications that could easily be incorporated to further the use of this device. For example, the sensing material used in the prototype (i.e., filter paper) can be replaced with material that remains intact for long periods while providing a quantitative measure of soil moisture properties—such as hydrophilic membranes that do not easily degrade in soil (e.g., glass fiber) and can be calibrated to develop a relationship between electrical resistance and water content/matric potential. Further, this device can be adapted to link to wireless sensing networks so that they can eventually be deployed in large numbers relatively easily, and at low cost and power demand. To facilitate this, individual SAS stems could be packaged with a micro-sized computer that processes and stores data, a low-power radio, and a small battery to create a "sensor node". The radio could then enable multiple nodes to communicate with each other and the "outside world."

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TABLES

Table 1. Cost comparisons for making 48 measurements using the SAS and TDR technique. Note the TDR costs are for a commercially available system sold by Campbell Scientific Inc., Logan, UT

SAS Prototype			TDR System	
Hardware	***Cost ($)***		***Hardware***	***Cost ($)***
PVC tubing (3 m)	10		Probes (48)	4,320
Filter paper	5		Reflectometer	3,500
Wire	20		Multiplexers (7)	3,500
Multiplexer	500		Datalogger	1,200
Data logger	1,200			
Labor to assemble four SAS stems	320			
Total Cost for 48 SAS Measurements	**2,055**		**Total Cost for 48 TDR Measurements**	**12,520**

FIGURE CAPTIONS

Figure 1. Components of a single stem of the prototype sensor array system (SAS). (A) sensor design and (B) location of sensors along the stem. The length of stem and the spacing between sensors can be adjusted for specific applications.

Figure 2. Setup for two tests used to evaluate the SAS. (A) Location of four SAS stems and TDR probes in a soil column. (B) Sketch and photograph of a field site in Berkeley that was instrumented with SAS stems and TDR probes at three locations. SAS stems extended into 0.60 m of soil and had sensors spaced at 0.05 m intervals.

Figure 3. TDR and SAS measurements along the length of a 0.60 m long column of soil. Note the legend in each chart indicating the type of measurement (i.e., 'T'-TDR, 'S1'-SAS) and the location (in meters) of each sensor relative to the soil surface. For each depth, the chart on the left shows the response before and during the ~36-hour infiltration event; the chart on the right is for the following 14-day period. In each case, the 'y' axis has been optimized to cover the range of measured response from each sensor.

Figure 4. Wetting-front travel along the vertical soil profile after water was introduced along the surface. (A) Elapsed time as detected by TDR probes and SAS sensors located at various depths. (B) Schematic showing the distance of the zone of influence of the sensors from the infiltration surface.

Figure 5. Qualitative assessment of saturation changes along a vertical soil column made simultaneously by four SAS stems (see figure 2A). The ‘x’ axis in each of the plots indicates time elapsed since the start of the release of ~18L of water at the surface. The ‘y’ axis is distance from the surface that sensors were located (as indicated by the dark horizontal lines). The ‘z’ axis, expressed as a color gradient, represents the saturation changes at a specific point as suggested by changes in measured resistance.

Figure 6. TDR and SAS response to soil moisture changes along a hillslope in Berkeley, California. The legend in each plot indicates location of site (U = upper, L = Lower) relative to Figure 2B, the distance (in meters) from surface to where the sensor is located, and the type of measurement (T = TDR, S =SAS).

Figure 7. Saturation changes as indicated by color gradients in three sites along a hillslope. As in Figure 5, the ‘y’ axis is distance from the surface that sensors were located (as indicated by the dark horizontal lines. The ‘z’ axis expressed as a color gradient represents the saturation changes at a point, as suggested by changes in measured resistance.

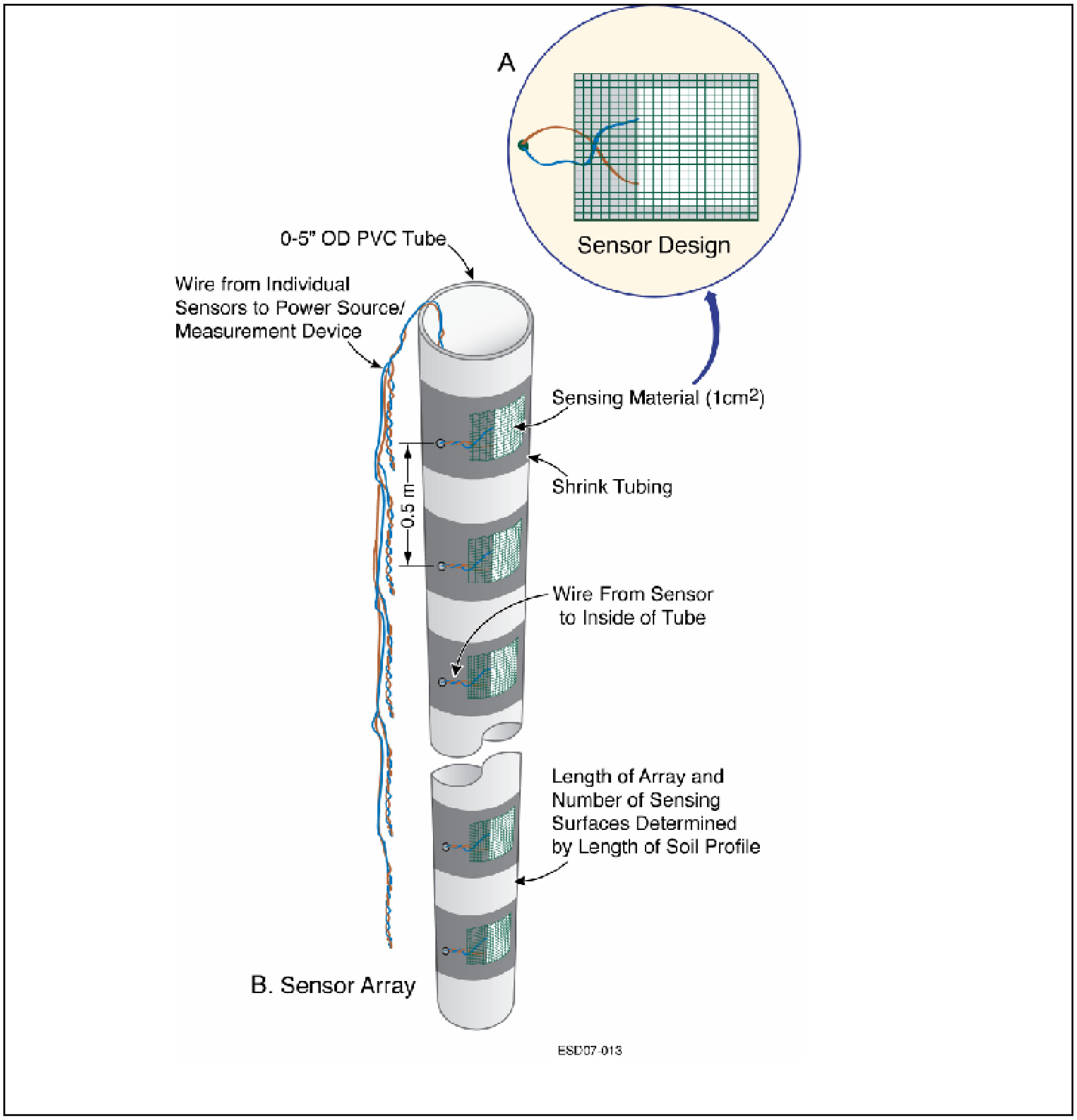
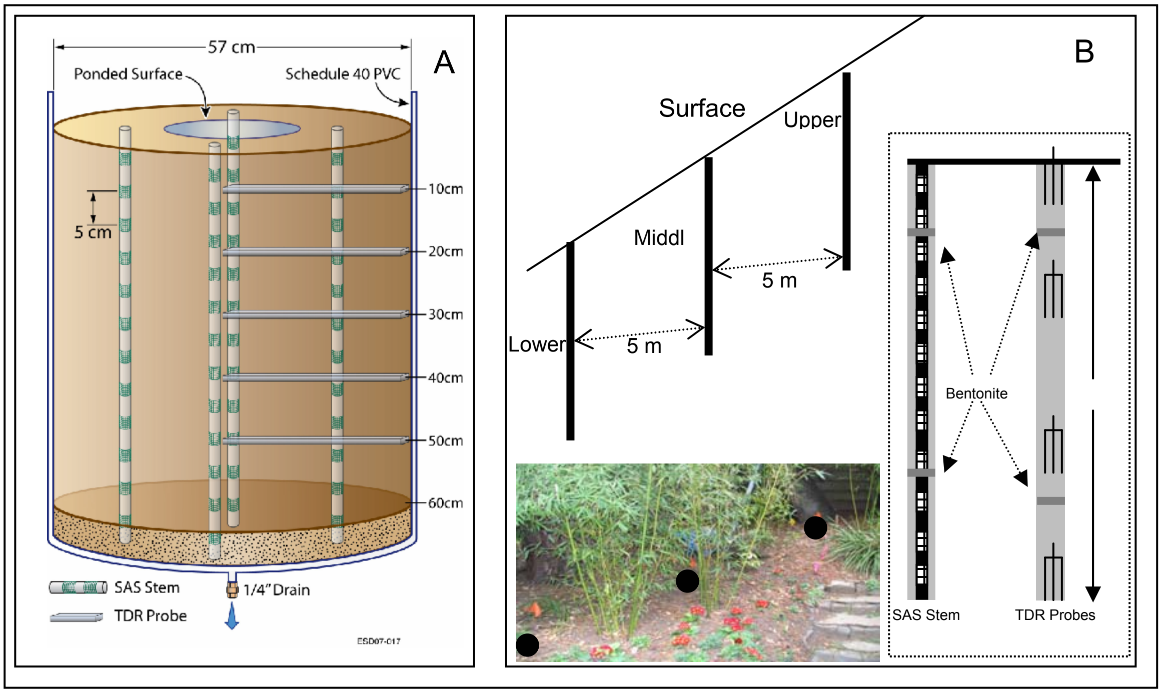

A
Sensor Design
0-5" OD PVC Tube
Wire from Individual
Sensors to Power Source/
Measurement Device
Sensing Material (1cm2)
Shrink Tubing
0.5 m
Wire From Sensor
to Inside of Tube
Length of Array and
Number of Sensing
Surfaces Determined
by Length of Soil Profile
B. Sensor Array
ESD07-013

Figure 1.



57 cm
Ponded Surface
Schedule 40 PVC
A
10cm
20cm
30cm
40cm
50cm
60cm
5 cm
SAS Stem
TDR Probe
1/4" Drain
ESD07-017
B
Surface
Upper
Middl
Lower
5 m
5 m
Bentonite
SAS Stem
TDR Probes

Figure 2.

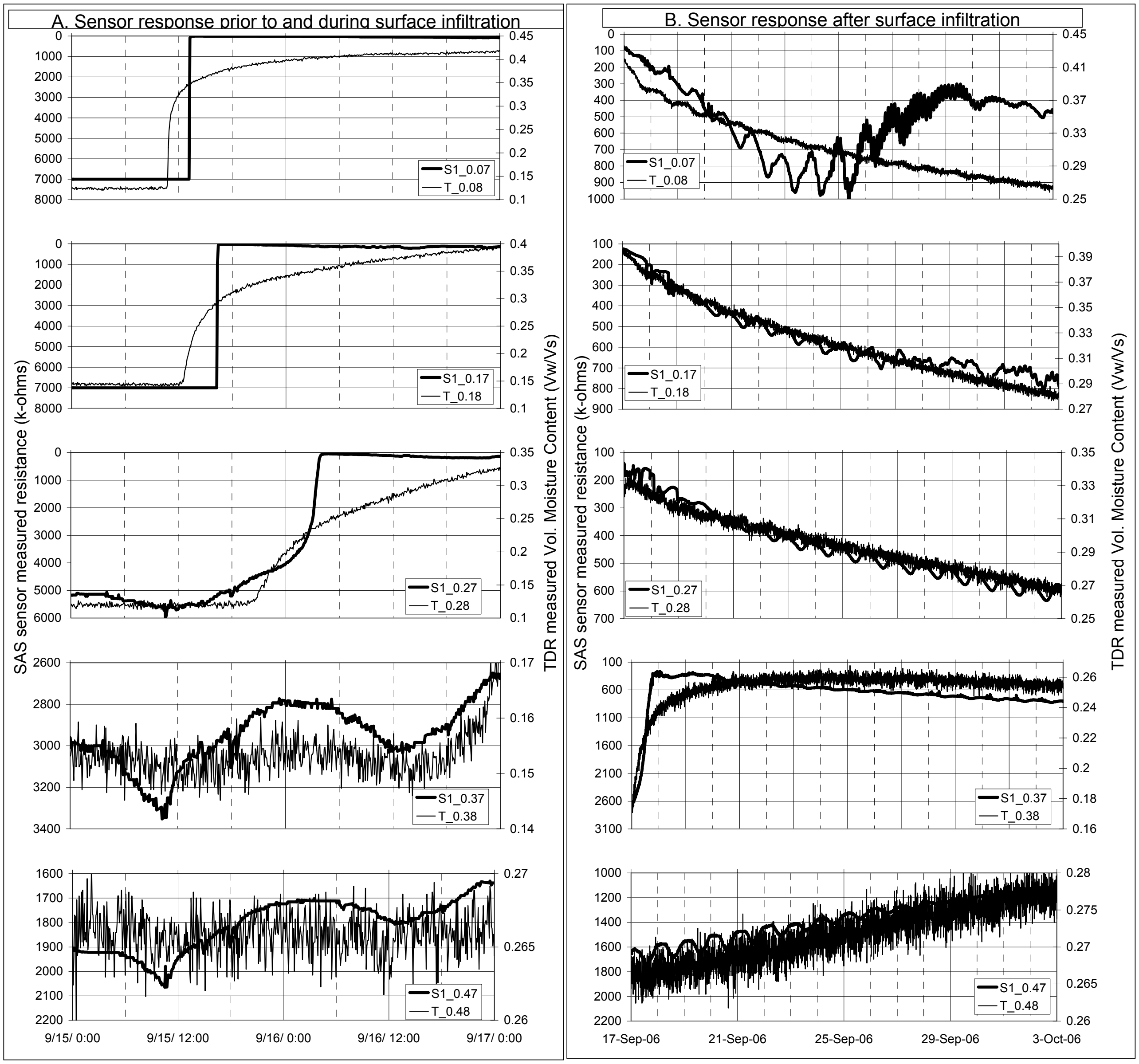

A. Sensor response prior to and during surface infiltration
B. Sensor response after surface infiltration
SAS sensor measured resistance (k-ohms)
TDR measured Vol. Moisture Content (Vw/Vs)
S1_0.07
T_0.08
S1_0.17
T_0.18
S1_0.27
T_0.28
S1_0.37
T_0.38
S1_0.47
T_0.48
9/15/ 0:00
9/15/ 12:00
9/16/ 0:00
9/16/ 12:00
9/17/ 0:00
17-Sep-06
21-Sep-06
25-Sep-06
29-Sep-06
3-Oct-06

Figure 3

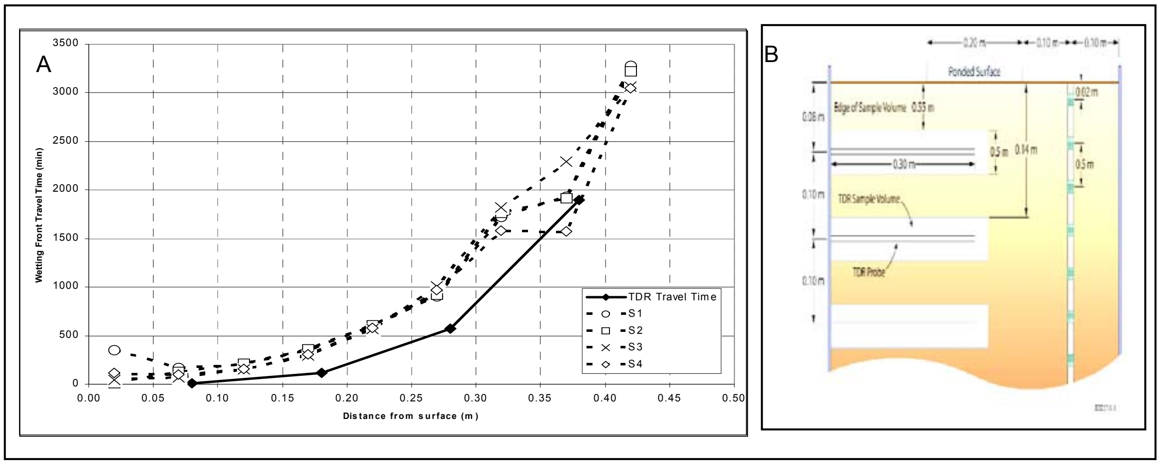


Figure 4

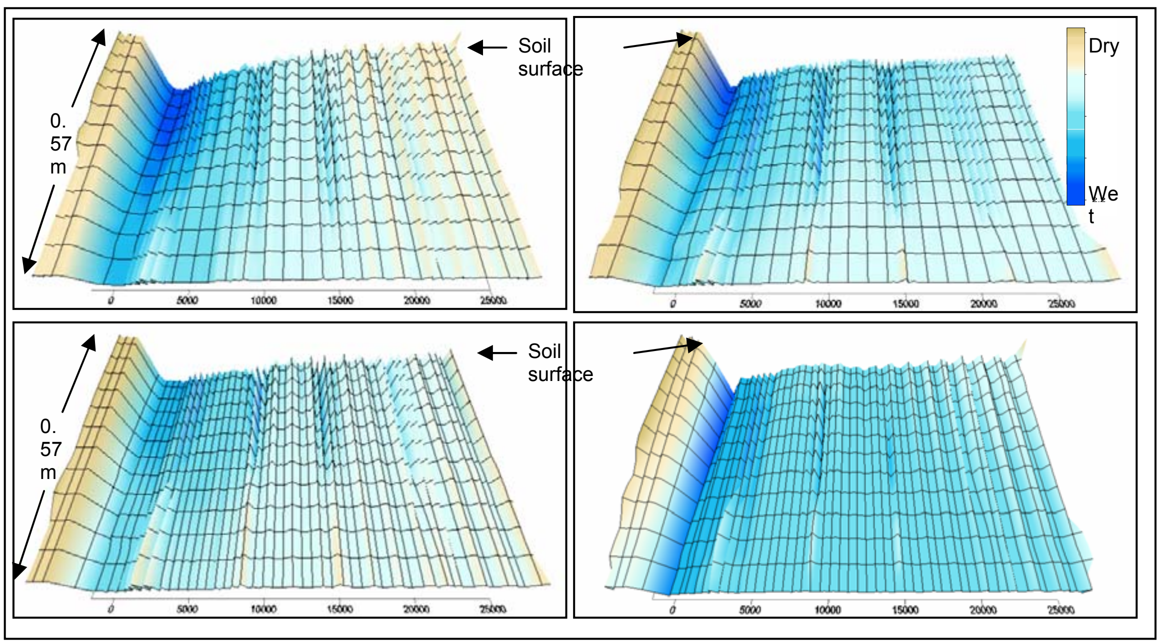
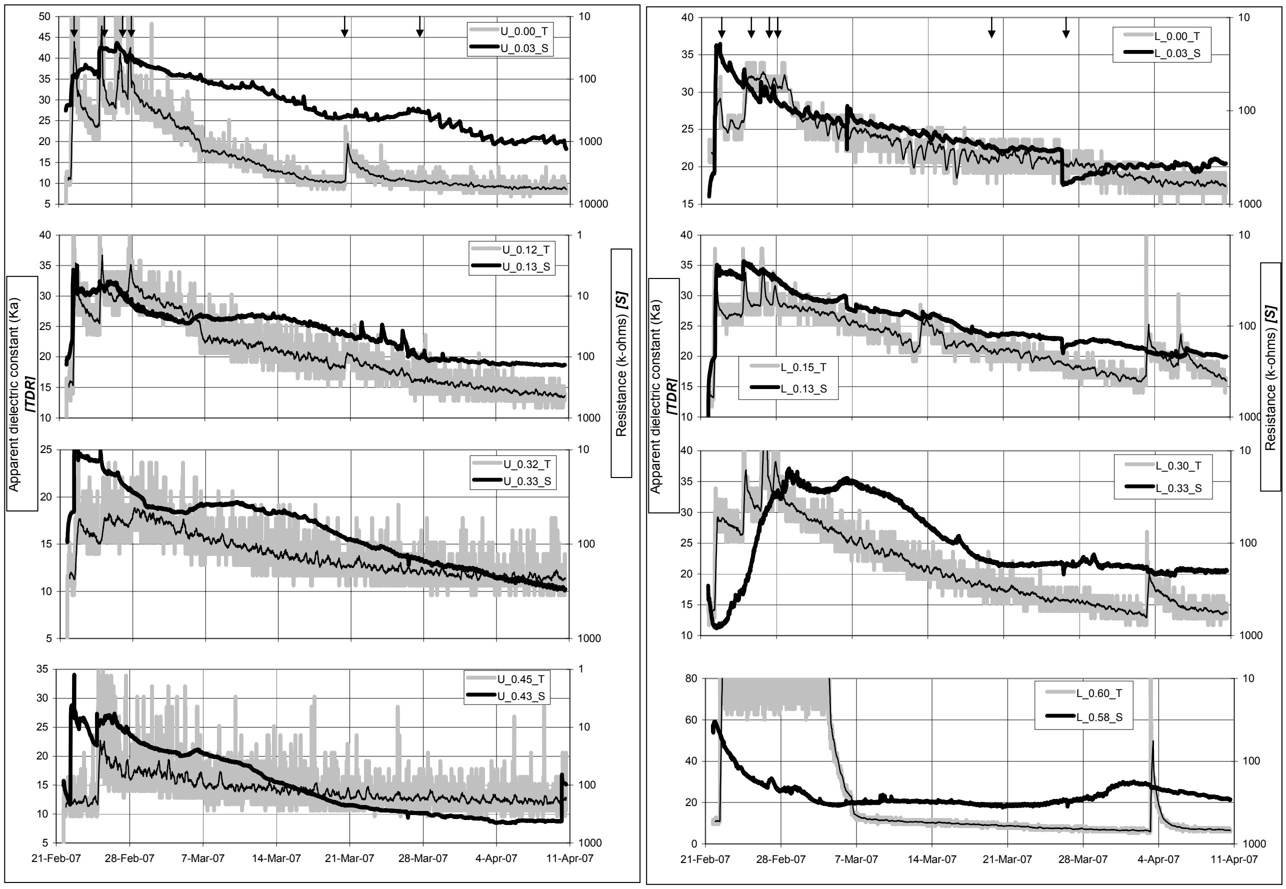


Figure 5



Apparent dielectric constant (Ka) [TDR]
Resistance (k-ohms) [S]
U_0.00_T
U_0.03_S
U_0.12_T
U_0.13_S
U_0.32_T
U_0.33_S
U_0.45_T
U_0.43_S
L_0.00_T
L_0.03_S
L_0.15_T
L_0.13_S
L_0.30_T
L_0.33_S
L_0.60_T
L_0.58_S
21-Feb-07
28-Feb-07
7-Mar-07
14-Mar-07
21-Mar-07
28-Mar-07
4-Apr-07
11-Apr-07

Figure 6

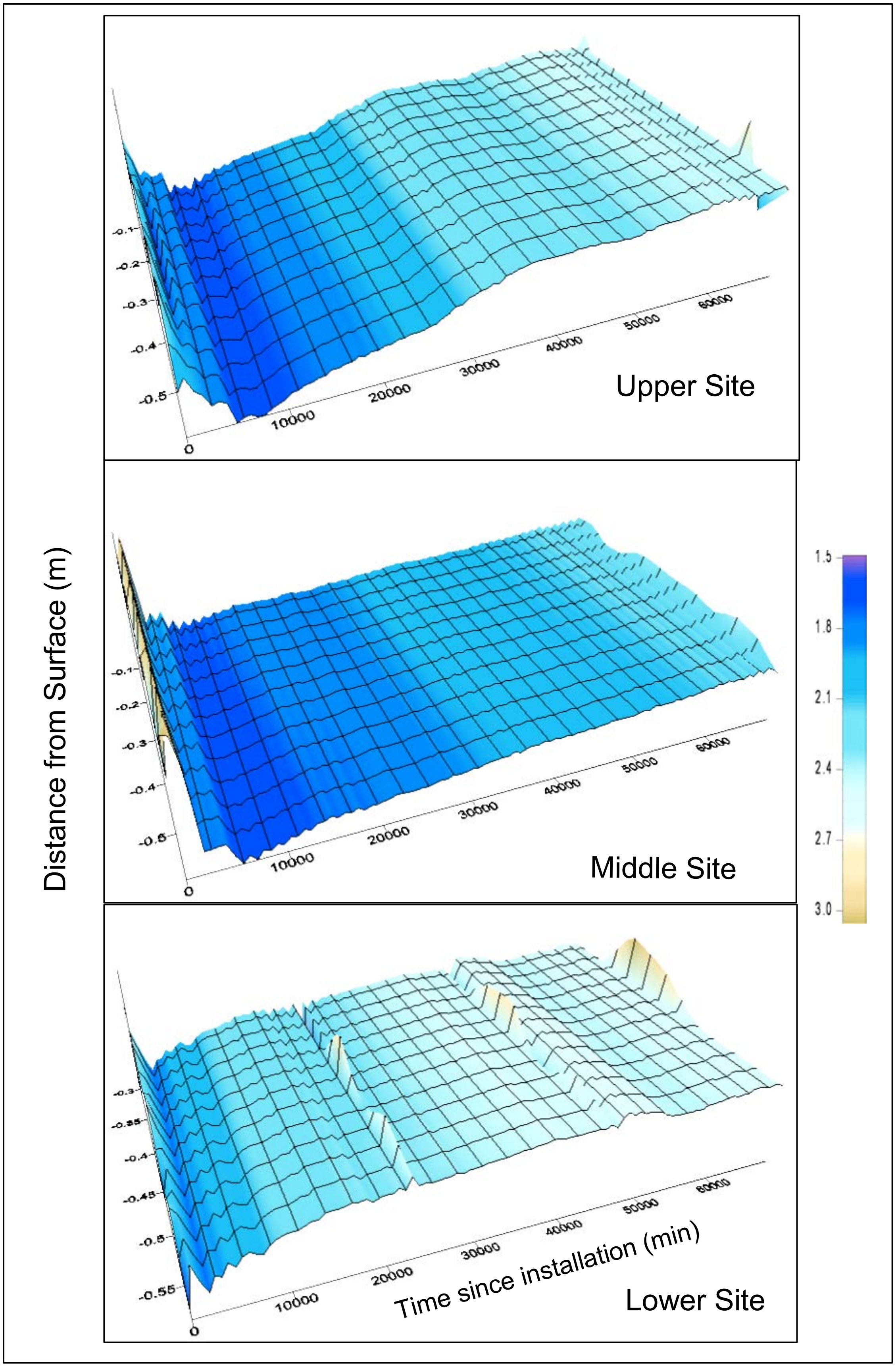

Distance from Surface (m)
Upper Site
Middle Site
Lower Site
Time since installation (min)
1.5
1.8
2.1
2.4
2.7
3.0

Figure 7